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# Search for 14.4 keV solar axions from M1 transition of $^{57}$Fe with CUORE crystals

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**Abstract.** We report the results of a search for axions from the 14.4 keV M1 transition from $^{57}$Fe in the core of the sun using the axio-electric effect in $TeO_2$ bolometers. The detectors are $5\times5\times5$ cm$^3$ crystals operated at about 10 mK in a facility used to test bolometers for the CUORE experiment at the Laboratori Nazionali del Gran Sasso in Italy. An analysis of 43.65 kg·d of data was made using a newly developed low energy trigger which was optimized to reduce the detectors energy threshold. An upper limit of 0.63 c·kg$^{-1}$·d$^{-1}$ was established at 95% C.L.. From this value, a lower bound at 95% C.L. was placed on the Peccei-Quinn energy scale of $f_a \geq 0.76 \times 10^6$ GeV for a value of S=0.55 for the flavor-singlet axial vector matrix element. Bounds are given for the interval $0.15 \leq S \leq 0.55$.

## Contents



# 1 Introduction

Quantum chromodynamics or QCD, largely accepted as the best theory describing strong interactions, contains one curious blemish known as "the strong CP problem". QCD predicts a large neutron electric dipole moment, of the order $|d_n| \approx 10^{-16}$ e·cm, whereas the experimental bound is $|d_n| \leq 2.9 \times 10^{-26}$ e·cm [1]. This fact puts an unnaturally small upper limit ($< 10^{-10}$) to the $\theta_{QCD}$ parameter, the strength of the CP violating term present in the QCD. In order to explain this small value Roberto Peccei and Helen Quinn proposed [2] that the QCD Lagrangian possessed an additional global U(1) symmetry which modified the CP-violating term to:

$$\mathcal{L}_\theta = (\theta_{QCD} - \frac{a}{f_a})\frac{g_s^2}{32\pi^2} G_a^{\mu\nu}\tilde{G}_{a\mu\nu}. \tag{1.1}$$

where $g_s$ is the strong coupling constant, $G_a^{\mu\nu}$ the gluon field, $a$ a new scalar field, and $f_a$ an energy scale. Non-perturbative effects induce a potential for the field $a$ that has a minimum at $a = f_a\theta_{QCD}$ which causes the spontaneous breaking of the global U(1) symmetry. As later shown by Weinberg and Wilczek [3], the spontaneous breaking symmetry produces a Nambu-Goldstone boson known as the axion.

The "standard" Peccei-Quinn axion with symmetry breaking scale of the order of the electro-weak scale is ruled out by experiments. However, other models of "invisible" axions which break the symmetry at much higher energies are still an interesting possibility, and the search of an axion mass in the range between $10^{-10}$ – $10^{-6}$ eV is a very active field of research. The possibility that the axion might be most or part of the dark–matter has reinforced even further the interest for this field [4].

The most common models are the so called hadronic or KSVZ axion model [5] and the GUT or DFSZ models [6]. In both cases, the mass of the axion is directly related to the axion's decay constant, $f_a$, the pion's mass $m_\pi$=135 MeV, the pion's decay constant $f_\pi \approx 92$ MeV, and the up-down quark mass ratio, $z$=0.56 [7], as follows:

$$m_a = \left(\frac{z}{(1+z+w)(1+z)}\right)^{\frac{1}{2}} \frac{f_\pi m_\pi}{f_a} = 6\ [eV]\Big(\frac{10^6}{f_a\ [GeV]}\Big). \tag{1.2}$$

where $w$=$m_u/m_s = 0.029$.

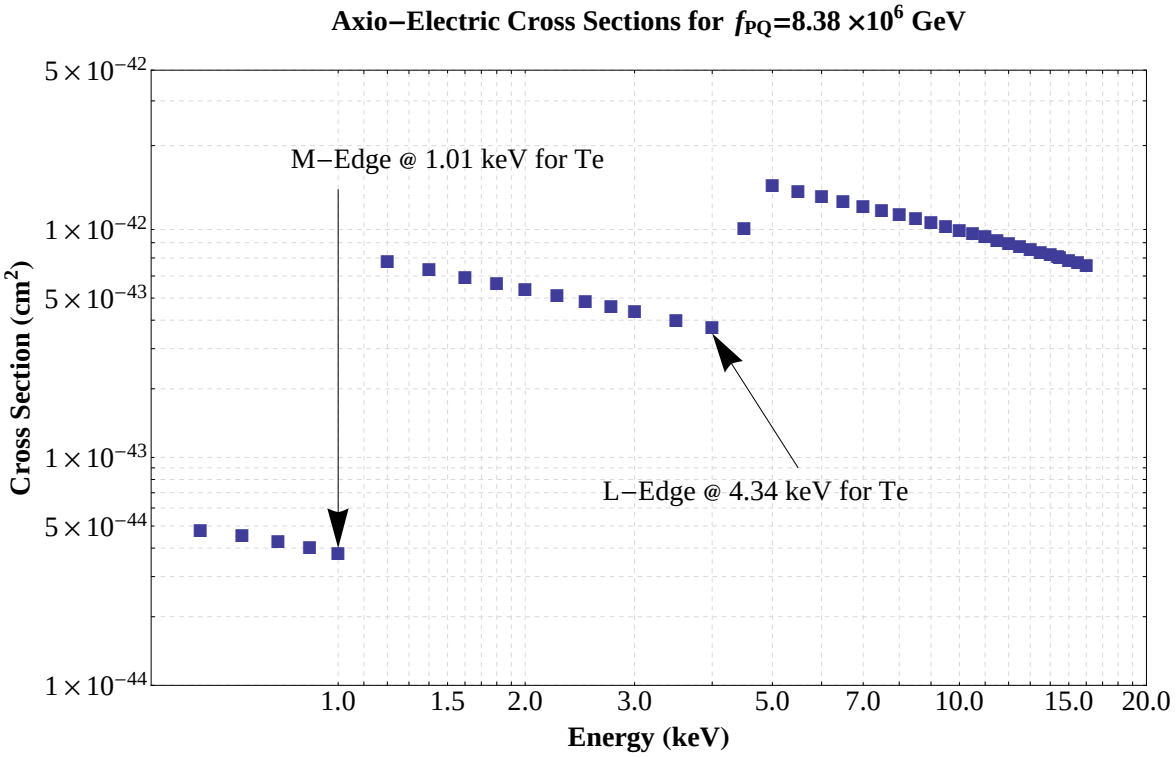


**Figure 1**. Axio-electric cross sections of $TeO_2$ in the energy range 0-20 keV using $f_a$=8.38×10$^6$ GeV.

The detection mechanism used in the present work is the axio-electric effect, which is the equivalent of a photo-electric effect with the absorption of an axion instead of a photon. The cross section, which can be seen in Fig. 1 for $TeO_2$, is given by [8]:

$$\sigma_{ae} = \frac{\alpha_{axion}}{2\alpha_{EM}}\left(\frac{\hbar\omega}{m_e c^2}\right)^2 \sigma_{pe} \tag{1.3}$$

$$\text{with,} \quad \alpha_{axion} = \frac{1}{4\pi}\left(\frac{2x'_e m_e c^2}{f_a}\right)^2. \tag{1.4}$$

For Eq. 1.4, $x'_e \approx 1$, $m_e c^2$ is the electron mass in GeV, $\alpha_{EM} = \frac{1}{137}$, and $\sigma_{pe}$ is the photo-electric cross sections for each element (taken from [9]).

The axion source in this search is the M1 transition produced by thermal excitation of $^{57}$Fe in the solar core. The isotope $^{57}$Fe is stable and has 2.12% natural abundance, yielding an average $^{57}$Fe density in the Sun's core of (9.0 ± 1.2) $10^{19}$ cm$^{-3}$. The uncertainty is mostly due to the different metal diffusion models in the core and is computed in [10]. The first excited state is at 14.4 keV, low enough to be thermally excited in the interior of the sun, which has an average temperature $kT \approx 1.3$ keV [11][12].

In this paper we rely on [12] for the determination of the expected axion flux and axion interaction rate in $TeO_2$ crystals. The 15% error in the knowledge of $^{57}$Fe density is taken into account.

The Lagrangian that couples axions to nucleons is:

$$\mathcal{L} = a\bar{\psi}_i\gamma_5(g_0\beta + g_3\tau_3)\psi. \tag{1.5}$$

**Table 1**. Detection Rates for $TeO_2$ (counts·kg$^{-1}$·d$^{-1}$)

| S\$f_a$(GeV) | $3.0\times10^5$ | $5.0\times10^5$ | $7.0\times10^5$ | $9.0\times10^5$ | $1.1\times10^6$ |
|---|---|---|---|---|---|
| 0.15 | 0.070 | 0.014 | 0.007 | 0.00273 | 0.00122 |
| 0.20 | 0.349 | 0.069 | 0.037 | 0.0136 | 0.00609 |
| 0.25 | 0.840 | 0.166 | 0.089 | 0.0327 | 0.01466 |
| 0.30 | 1.542 | 0.304 | 0.164 | 0.0601 | 0.02694 |
| 0.35 | 2.457 | 0.485 | 0.262 | 0.0958 | 0.04293 |
| 0.40 | 3.585 | 0.707 | 0.382 | 0.140 | 0.06263 |
| 0.45 | 4.924 | 0.972 | 0.525 | 0.192 | 0.08604 |
| 0.50 | 6.476 | 1.278 | 0.690 | 0.253 | 0.11316 |
| 0.55 | 8.241 | 1.627 | 0.878 | 0.321 | 0.14398 |

Here, $g_0$ and $g_3$ are the iso-scalar and iso-vector coupling constants, and $\tau_3$ is a Pauli matrix. The axion-nucleon coupling constants are defined by [12]:

$$g_0 = -7.8 \times 10^{-8}\Big(\frac{6.2 \times 10^6 \text{GeV}}{f_a}\Big)\Big(\frac{3F - D + 2S}{3}\Big) \tag{1.6}$$

$$g_3 = -7.8 \times 10^{-8}\Big(\frac{6.2 \times 10^6 \text{GeV}}{f_a}\Big)\Big((D + F)\frac{1 - z}{1 + z}\Big) \tag{1.7}$$

where F≈0.48 and D=0.77 are invariant matrix elements of the axial current [13]. The Spin-Muon Collaboration lists a range for S of $0.15 \leq S \leq 0.50$ at 95% C.L [14] while Altarelli *et. al* give the range $0.37 \leq S \leq 0.53$ [15]. Both $g_0$ and $g_3$ contribute to the axion branching ratio. This is critical to the formulation of the energy loss within the sun due to axion emission. Combined with the flux rates listed in Ref. [8] the axion detection rates were determined and listed Table 1.

## 2 Experiment

In the analysis shown in the present work we will focus on the results from a specific R&D run dedicated to the CUORE experiment.

CUORE will be an array of 988 tellurium dioxide crystals, each with size $5 \times 5 \times 5$ cm$^3$ and weight 750 grams, which will be operated as bolometers at a temperature of about 10 mK to search for neutrino-less double beta decay of $^{130}$Te and other rare events. A description of the CUORE technique and the basic principles behind bolometers is given in [16], [17], [18], and [19].

The crystals to be used for CUORE are produced at the Shanghai Institute for Ceramics of the Chinese Academy of Science (SICCAS), and are shipped to the Laboratori Nazionali del Gran Sasso (LNGS) located in Assergi, Italy. The crystals are produced and shipped in batches to LNGS. Four crystals are taken at random from each batch to measure their radioactive contamination levels and evaluate their performance at low temperature. Each one of these runs is called a Cuore Crystal Validation Run, or CCVR [20]. This paper will analyze data from the second run, known as CCVR2.

The four $TeO_2$ crystals have a total active mass of 3 kg and are mounted in a specially designed copper frame which is placed inside a dilution refrigerator at LNGS. The cryostat

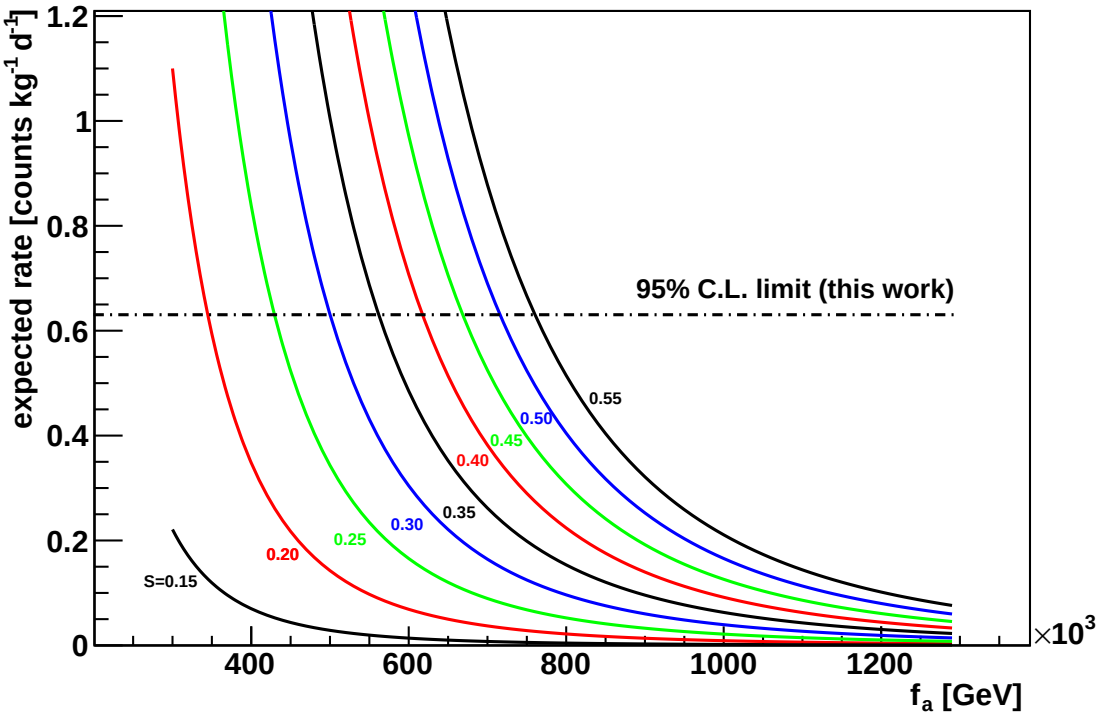


**Figure 2**. Expected rate in the axion region as a function of the $f_a$ axion constant for different values of the nuclear S parameter. The horizontal line indicates the upper limit obtained in this work.

is maintained at a working temperature of approximately 8-10 mK throughout the runs duration.

Attached to each CCVR crystal are two neutron transmutation doped germanium semiconductors, NTDs. CCVR2 collected data for a total of 19.4 days for a total of 43.65 kg·d. Calibrations were performed in the middle and end of the run with a $^{232}$Th $\gamma$ source inserted inside the Pb shielding, close to the cryostat outer vacuum vessel.

Previous CUORE R&D experiments, such as CUORICINO [16][21], had bolometers whose typical threshold was 50 keV. Since the Q-value for $^{130}$Te is at 2527 keV [22][23], a threshold at 50 keV was more than satisfactory for $\beta\beta$-decay searches. However, to investigate physical events at lower energies, new procedures were needed to lower the energy threshold. For this reason a special low–energy trigger was developed and applied offline, exploiting the fact that the standard CUORE DAQ used in the CCVR runs collects data continuously and with no hardware trigger using 125 Hz 18-bits digitizers [24].

This trigger algorithm maximizes the signal to noise ratio by filtering the data with a known power spectrum and a reference signal shape. A full description of it is given in [25]. More details can be found in [26].

## 3 Results

In order to reject thermal and microphonic noise, the pulses are selected by applying cuts on the pulse shape parameters. The efficiency of these cuts must therefore be taken into account in the analysis. As usually done in Cuoricino and in all CCVR runs, a calibrated current pulse is sent every 30 minutes to a small resistor (heater) that is glued on each crystal. This calibration pulse is used to correct for temperature variations in the cryostat that change the response of the bolometer and therefore its signal amplitude. It is also used to measure the detection efficiency of the crystals.

The detection efficiencies ($\epsilon_D$) were measured using the heaters [27][28][29] through a dedicated measurement performed at the end of the data-taking. The equivalence of the bolometers response to particle and heater pulses was demonstrated via a MonteCarlo simulation [30] that allows to infer $\epsilon_D$ for the bolometer without the heater. Since the detection capability may vary with time, the fluctuation of the peak rate with time (11%) of the lowest energy $\gamma$ line (a 4.7 keV line described below) can be used as an (over)estimate of the systematic error on the detection efficiency [26].

The estimated values of $\epsilon_D$ are $0.91 \pm 0.10$ for B1 and $0.83 \pm 0.09$ for B2 and B3, dominated by the systematics. The pulse shape cut efficiencies have been evaluated on the 4.7 keV peak and are equal to 1.

The low energy spectrum, below 50 keV, is shown in Fig. 3. For this work we choose to include only the channels whose thresholds are lower than 5 keV as to include the peak at 4.7 keV. The physical interpretation of this peak is still being analyzed, but the lack of a full understanding of its origin has no consequence on the present work, because we used its width only to determine the energy resolution in the 14.4 KeV region.

Energy calibration in this very low energy region is not done with the $^{232}$Th lines, which are normally used for higher energy studies. The energy region between 2.5 and 300 keV is calibrated using a set of metastable Te lines that result from cosmogenic activation. The crystals spend a few weeks above ground while they are being shipped by sea[1] between the production site in Shangai, China and arrival at the underground storage site at LNGS. The main lines used in the calibration for present work are reported in Table 2.

| Energy [keV] | Source | Life-Time (days) |
|---|---|---|
| 30.4912 | Sb X-ray | – |
| $88.26 \pm 0.08$ | $^{127m}$Te | $109 \pm 2$ |
| $105.50 \pm 0.05$ | $^{129m}$Te | $33.6 \pm 0.1$ |
| $144.78 \pm 0.03$ | $^{125m}$Te | $57.40 \pm 0.15$ |
| $247.5 \pm 0.2$ | $^{123m}$Te | $119.7 \pm 0.1$ |
| $293.98 \pm 0.04$ | $^{121m}$Te | $154 \pm 7$ |

**Table 2**. List of $\gamma$ lines from meta–stable Te isotopes used in this analysis for the energy calibration in the energy region between 2.5 and 300 keV. The lines are available from cosmogenic activation of Te during shipment, and have half–lives spanning from 33.6 days and 119.7 days.

[1]The shipment of two (out of four) crystals was actually made by airplane, which induces a slightly higher activation.

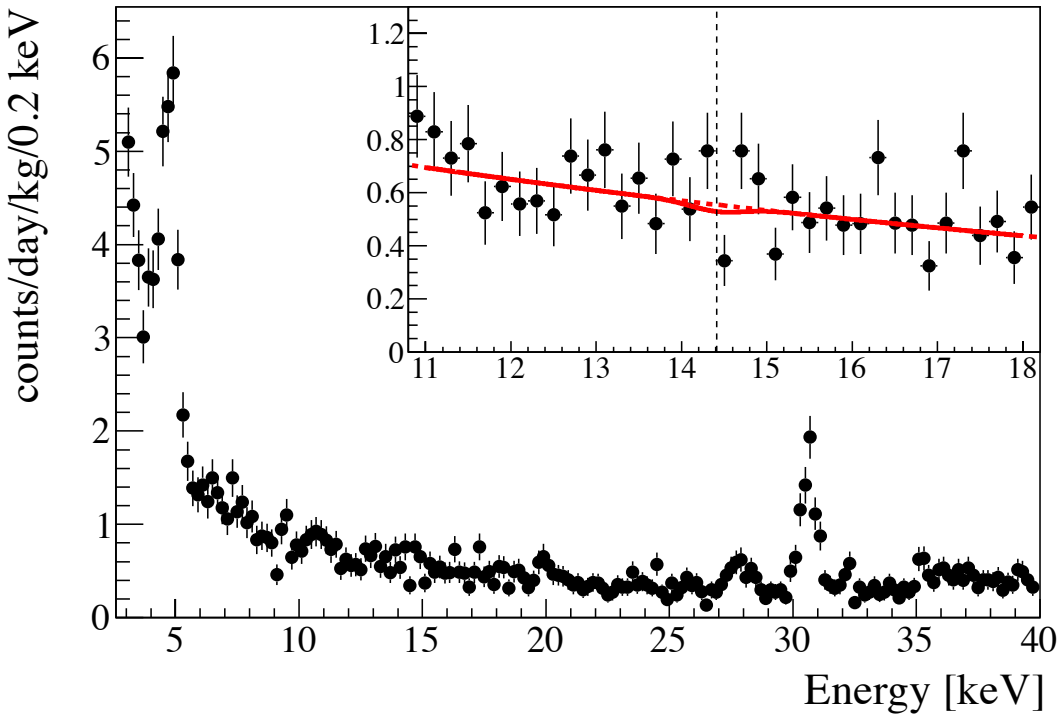


**Figure 3**. Energy spectrum for the low energy region between threshold and 40 keV. The two peaks at 4.7 keV and 30.49 keV are those used to study the energy resolution at low energy. The axion region around 14.4 keV is magnified in the inset with the fit result shown as red curve. No peak is observed at 14.4 keV, the M1 transition energy of $^{57}$Fe for solar axions.

As a further check of the calibration, we faced to a bolometer a $^{55}$Fe source. The X- rays produced, with nominal energy between 5.888 and 6.490 keV, were shifted by only 48±16 eV.

The energy calibration is obtained from a third degree polynomial fit. The complete low energy spectrum is modeled with two exponentials, one for the region lower than 5 keV, one for the background above 7 keV, and also a Gaussian indicative of the peak around 4.7 keV:

$$f_{global}(E) = \alpha_1 \cdot e^{-\beta_1 \cdot E} + \alpha_2 \cdot e^{-\beta_2 \cdot E} + \frac{\alpha_3}{\sqrt{2\pi}\sigma} e^{\frac{(E-E_{4.7})^2}{2\sigma^2}}. \tag{3.1}$$

Extracting the fit parameters obtained using Eq. 3.1 applied to Fig. 3 yields $\sigma_{4.7} = 0.31 \pm 0.04$ keV. This value is then applied to the fit in the axion region from 11 to 18 keV. It is not as reasonable to extract limits based on the overall global fit since the fluctuation in the background is more pronounced in the spectrum shown in inset of Fig. 3, the region where the 14.4 keV axion interaction would be observed.

To this spectrum a "modified" fit is applied to extract limits on the axion's coupling constant and mass. First, the background needs to be modeled. The background function appears to be flat, but to ensure validity first, second and third order polynomials are tested along with an exponential. For each, a Pearson's-$\chi^2$ test is performed to determine the most

accurate background fit. We find that an exponential models the background most accurately, so this is used with a Gaussian function to represent the 14.4 keV axion peak. The variance for the Gaussian will be the previously found $\sigma_{4.7}$. The bolometers resolution is not dominated by signal fluctuations and we know that the energy dependence of the detector resolution is weak; no significant change is expected from 4.7 keV to 14.4 keV[2]. The signal plus background model which we have used in the fit is therefore:

$$f_{axion}(E) = a_1 e^{b \cdot E} + \frac{a_2}{\sqrt{2\pi}\sigma_{4.7}} Exp\Big[\frac{(E - E_{14.4})^2}{2\sigma_{4.7}^2}\Big] \tag{3.2}$$

No excess in the axion region is observed. We set therefore a lower bound on the axion decay constant $f_a$ based on the background fluctuations.

There are 116±12 counts in the energy interval between $[E_{14.4} - \sqrt{2}\sigma_{4.7}, E_{14.4} + \sqrt{2}\sigma_{4.7}]$, corresponding to 2.65±0.27 c·kg$^{-1}$·d$^{-1}$.

Assuming Poisson statistics and including the combined effect of a fluctuation of the background and of the 15% systematic error induced by cut efficiencies and the uncertainty in the solar axion rate, we assert that the axion detection rate is $\leq 0.63$ c·kg$^{-1}$·d$^{-1}$ at a 95 % C.L. Using S=0.55, this places a bound on the axion coupling constant of $f_a \geq 0.76 \times 10^6$ GeV at 95% C.L.

The 95% C.L. and the 1-$\sigma$ bounds as a function of the nuclear S parameter are shown in Fig. 4.

## 4 Summary and Conclusions

An experimental search was performed for axions from the solar core from the 14.4 keV M1 ground-state nuclear transition in $^{57}$Fe. The detection technique employed a search for a peak in the energy spectrum at 14.4-keV when the axion is absorbed by an electron via the axio-electric effect. The cross section for this process is proportional to the photo-electric absorption cross section for photons. In this pilot experiment 43.65 kg·d of data were analyzed resulting in a lower bound on the Peccei-Quinn energy scale of $f_a \geq 0.76 \times 10^6$ GeV for a value for the flavor-singlet axial vector matrix element of S=0.55; bounds are presented in a graph for values $0.15 \leq S \leq 0.55$.

With the numbers quoted in the text, the limit on $f_a$ translates into a mass limit $m_a < 6$ eV, significantly more stringent than in recent results obtained with $^{57}$Fe detectors [31] and by the Borexino experiment [32] [33].

The CUORE experiment will have about 740 kg $TeO_2$. With live–time of 5 live years the exposure will be $1.4 \times 10^6$ kg·d. With a similar background as the one reported here the expected sensitivity on $f_a$ will be roughly increased by an order of magnitude.

## 5 Acknowledgments

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[2]We have also checked the resolution at the 30.5 keV X-ray line shown in Table 2, finding a very consistent value.

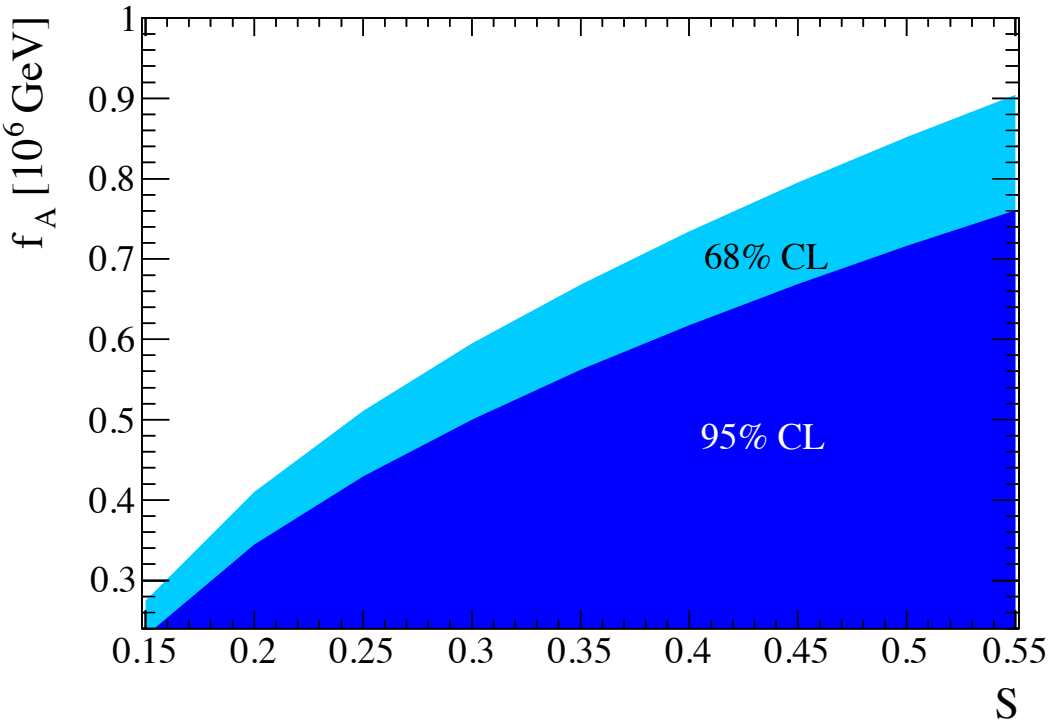


**Figure 4**. Exclusion plots for one and two sigma confidence levels for $f_a$ as a function of the nuclear S parameter values (see Eq. 1.7 for the meaning of the S parameter).

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